Uranium enrichment

12

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12.1 Introduction

12.1.1 What is uranium enrichment?

Naturally occurring uranium comprises about 99.29% of the isotope ^{238}U (146 neutrons, 92 protons) and 0.71% of the isotope ^{235}U (143 neutrons, 92 protons).

^{238}U is mildly radioactive, undergoing alpha decay to ^{234}Th, but it is not fissile, that is, it cannot be used on its own to sustain a nuclear chain reaction.

^{235}U, on the other hand, is a less stable isotope that undergoes fission when a thermal neutron collides with the nucleus. More neutrons are emitted and, in the right quantity and concentration, ^{235}U is capable of sustaining a nuclear chain reaction; for example, as is required for a power generating nuclear reactor.

Uranium enrichment is the name given to any isotope separation process applied to natural uranium resulting in a product in which the concentration of ^{235}U is increased above the natural concentration of 0.71%.

The capacity of any equipment or installation to enrich uranium in measured in separative work units (SWUs).

12.1.2 What is a SWU?

Separative work performed to enrich uranium is defined by a mathematical formula (see next), but in essence it is a measure of work performed by a process to take a quantity of feed material at a certain ^{235}U concentration and convert it into a quantity of enriched product with a higher ^{235}U concentration and a balancing quantity of depleted "tails" with a lower ^{235}U concentration.

An example is shown in Fig. 12.1 where the feed is 0.71% ^{235}U, enriched product is 4% ^{235}U, and depleted tails are 0.3% ^{235}U.

Precise calculation of SWUs involves differential equations. In ordinary practice, however, the following equation can be used:

$$S = P(2xp - 1)\ln\frac{xp}{1-xp} + T(2xt - 1)\ln\frac{xt}{1-xt} - F(2xf - 1)\ln\frac{xf}{1-xf}$$

where:

S is the effort in SWUs,
P is the mass of the product, the enriched uranium,

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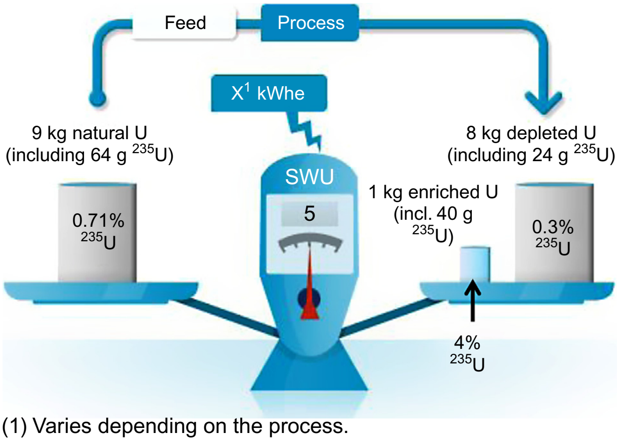


Figure 12.1 Enrichment calculation.
Source: AREVA.

T is the mass of the tails,
F is the mass of the feedstock,
xp is the assay of the product,
xt is the assay of the tails,
xf is the assay of the feedstock.

For a detailed theoretical explanation, see Cohen (1951).

The dimension of SWU is mass so:

1 SWU = 1 kg SWU

1000 SWU = 1000 kg SWU = 1 tSWU

SWU calculators are available on the Internet and as smartphone apps (search: SWU calculator).

A typical large nuclear power plant with an electrical output of 1300 MW requires about 25 t pa of enriched uranium with ^{235}U concentration of 4%. This is produced from about 210 t of natural uranium feed using about 120 tSWU. An enrichment facility with a capacity of 1000 tSWU pa is therefore able to enrich uranium sufficient to fuel about eight large nuclear power plants.

12.1.3 Who needs uranium enrichment services?

Uranium enrichment services are needed by entities that operate nuclear power plants. An up-to-date tabulation of World Nuclear Power Reactors can be found on the World Nuclear Association (WNA) website (www.world-nuclear.org/Info/Facts-and-Figures/World-Nuclear-Power-Reactors-and-Uranium-Requirements). As of February 2015, 438 civil power reactors were listed as operable.

Not all power reactors historically or in operation today require enriched uranium. For example, the first generation of gas-cooled power reactors commissioned in the United Kingdom 1956–71 (the magnox fleet) used natural assay uranium metal fuel. Pressurized heavy water reactors currently operated in a number of countries (Canada, China, South Korea, Romania, Argentina, Pakistan, and India) can utilize natural assay uranium fuel.

Enriched uranium is used by some governments for naval propulsion. Highly enriched uranium (HEU) has, and can be, used for weapons. Both these topics are outside the scope of this chapter.

The boundary of civil enrichment for nuclear power generation is generally considered to be 20% ^{235}U. Typically, to date, most reactors require enrichments up to 5% ^{235}U.

Research reactors can also use small quantities of enriched uranium. A database of research reactors around the world can be found at the International Atomic Energy Agency (IAEA) website (www.iaea.org, or Google nucleus.iaea.org/RRDB/RR/ReactorSearch.aspx). Historic and some current research reactors have used HEU. Globally there is an ongoing drive to convert research reactors to use low-enriched uranium (LEU) (<20% ^{235}U). More on this topic can be found at www.world-nuclear.org/Info/Non-Power-Nuclear-Applications/Radioisotopes/Research-Reactors/ and https://www.iaea.org/OurWork/NE/NEFW/Technical-Areas/RRS/conversion.html.

Using projections of the number of civil power reactors operating globally including considerations of new reactor construction and commissioning, reactor shutdowns, power upgrades, maintenance, and refueling outages, various scenarios for forward demand for civil nuclear enrichment services can be forecast. Fig. 12.2 shows the WNA low, reference, and high case forward forecasts. Fig. 12.3 shows a comparison of a number of published reference case forward forecasts.

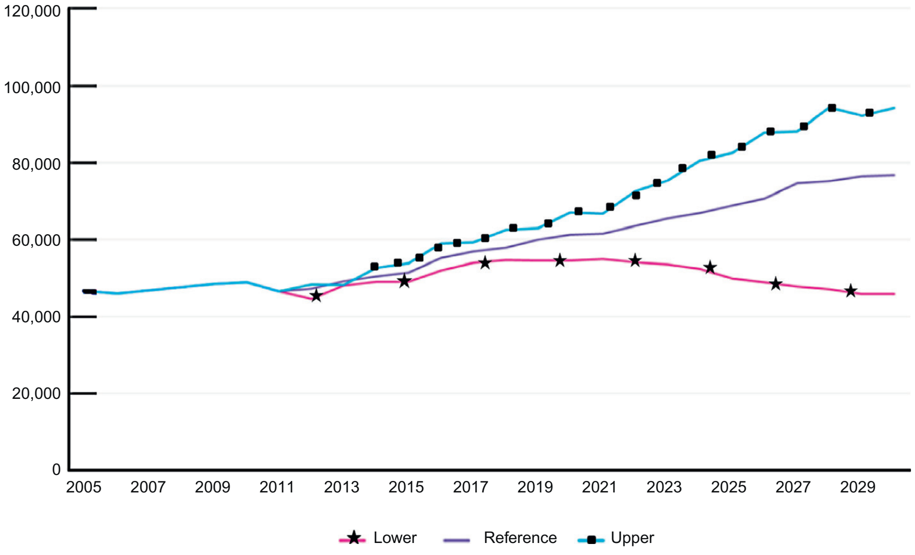


Figure 12.2 WNA enrichment demand scenarios.
Source: WNA.

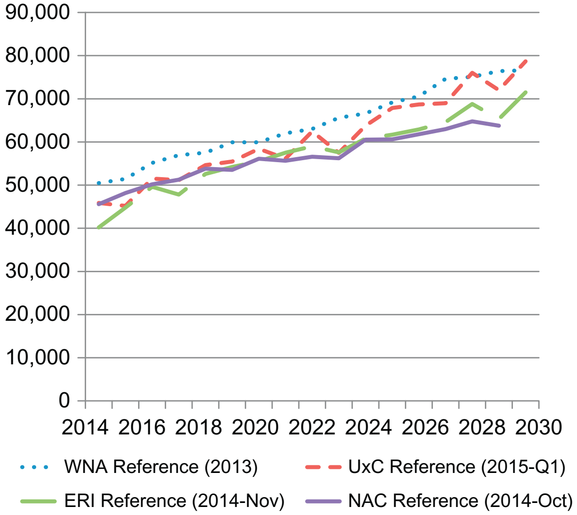


Figure 12.3 Comparison of demand scenarios.

In the reference cases, demand is forecast to rise from approximately 50,000 tSWU pa in 2015 to 60,000 tSWU pa by 2025.

Other nuclear materials can be used as fuel for power reactors, specifically plutonium mixed with uranium known as mixed oxide (MOX) fuel and thorium. Use of MOX is factored into the uranium enrichment demand forecasts. Thorium is not yet used routinely.

12.2 How is uranium enriched?

12.2.1 Current technology and civil facilities

All major commercial civil enrichment facilities today employ some form of gas centrifuge to achieve isotope separation (ie, enrichment) of ^{235}U from ^{238}U. To be suitable for enrichment in a gas centrifuge, uranium that has been mined is concentrated, purified, and chemically converted into uranium hexafluoride (UF_6), a compound of uranium that can easily be turned into a gas when heated for feeding to centrifuges.

Since the inception of uranium enrichment on an industrial scale in the 1950s, uranium isotope separation has predominantly utilized the "uranium hexafluoride" route and global industrial infrastructure to support uranium enrichment, historic and current, is built around conversion of mined uranium to uranium hexafluoride.

Disruptive technology could emerge to challenge this current norm, but it would require very large investment and changes to currently established processes and logistics.

12.2.2 Principles of a gas centrifuge

A gas centrifuge is a cylindrical device that spins at very high speed in a vacuum. When, for example, natural uranium hexafluoride is introduced into a gas centrifuge, the heavier ^{238}U containing molecules tend to migrate to the outer volume of the cylinder and the molecules incorporating the lighter ^{235}U tend to concentrate in the central volume (Fig. 12.4).

The degree of separation achieved by a single machine is small, so the process needs to be repeated hundreds of times to achieve ^{235}U concentrations in final product up to 5% assay required for typical nuclear power plants.

In industrial facilities, many machines are connected in series and in parallel trains to achieve the required enrichment of uranium hexafluoride feedstock in tonne quantities.

The configuration of machines to perform repeated isotope separations is known as a cascade. A representation of a cascade is shown (Fig. 12.5), together with a picture of an industrial installation (Fig. 12.6).

Feedstock is delivered to enrichment facilities from the facilities where it has been converted into uranium hexafluoride in International Standard “48Y” transport cylinders (Fig. 12.7). Enriched product, also in the form of uranium hexafluoride, is generally collected in International Standard “30B” transport cylinders (Fig. 12.8). Depleted tails, again in the form of uranium hexafluoride, is collected in 48Y-type cylinders.

Isotope separation in a gas centrifuge is a purely physical process, no chemical transformation occurs; the feed material is uranium hexafluoride, the product and tails are also uranium hexafluoride.

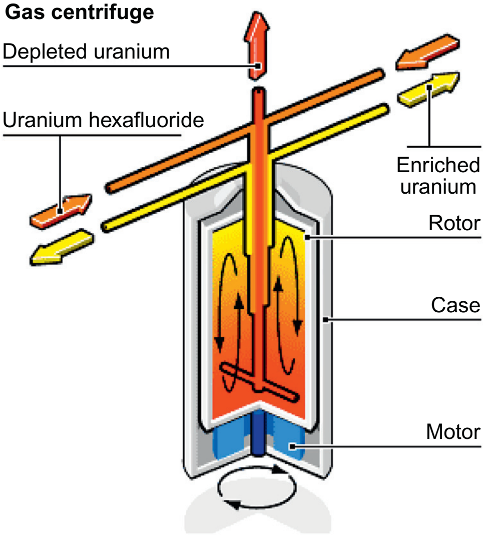


Figure 12.4 Gas centrifuge.
Source: uraniumworld.

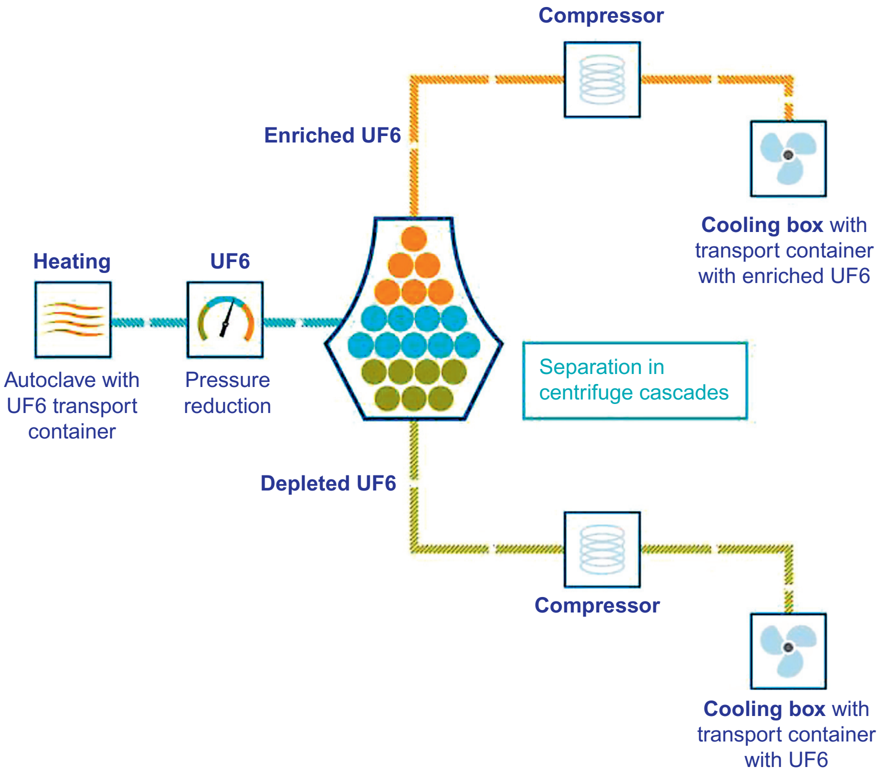

Compressor
Enriched UF6
Cooling box with transport container with enriched UF6
Heating
UF6
Autoclave with UF6 transport container
Pressure reduction
Separation in centrifuge cascades
Depleted UF6
Compressor
Cooling box with transport container with UF6

Figure 12.5 Representation of a cascade.
Source: URENCO.

Initial conversion of mined uranium to uranium hexafluoride is carried out in a variety of facilities prior to enrichment. Enriched product is subsequently deconverted, for example, to uranium dioxide, in a variety of facilities ahead of being fabricated into various designs of nuclear fuel elements for nuclear power plants.

Fig. 12.9 shows where uranium enrichment fits into the nuclear fuel cycle.

12.2.3 Current enrichment facilities: The main primary suppliers

12.2.3.1 URENCO

URENCO is a British/Dutch/German owned uranium enrichment company with its headquarters near London. URENCO operates four enrichment plants: Capenhurst, near Chester in the United Kingdom, Almelo in the Netherlands, Gronau in Germany, and Eunice, near Hobbs, New Mexico, United States. The combined reported enrichment capacity of the plants is 18,000 tSWU pa, (Fig. 12.10).

All the plants use gas centrifuge technology. The majority of the centrifuges are TC12-type machines. The most advanced TC21 machines are installed in a proportion of the cascades in the Gronau, Germany, and Eunice, US facilities.

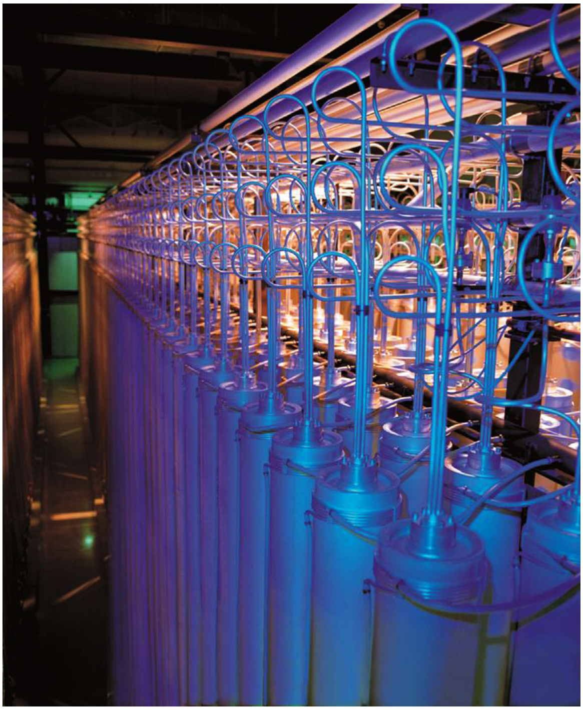


Figure 12.6 Picture of cascade.
Source: URENCO.

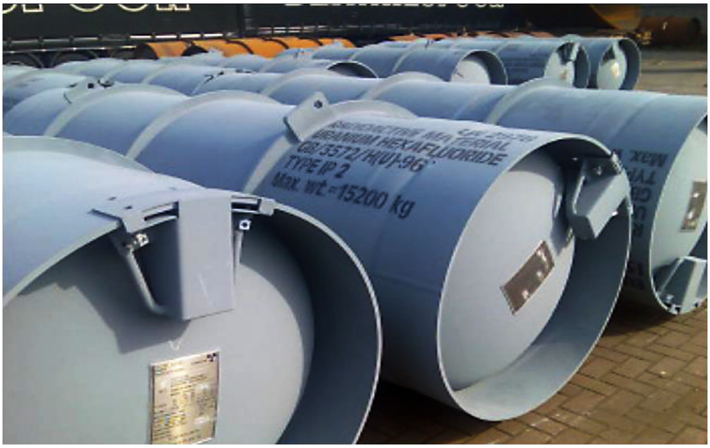


Figure 12.7 Picture of 48Y-type cylinders.
Source: NNSA.

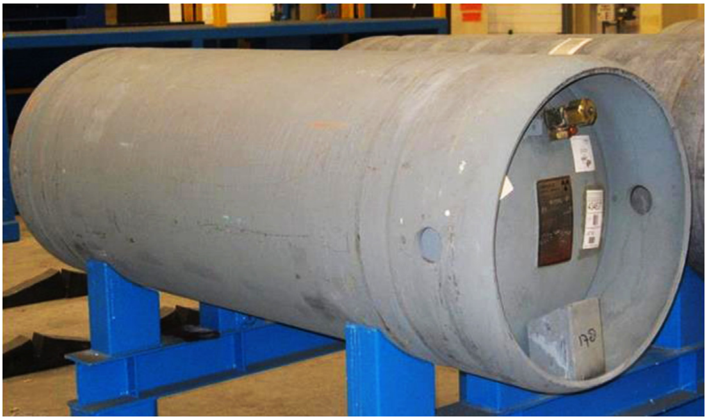


Figure 12.8 Picture of 30B-type cylinder.
Source: NNSA.

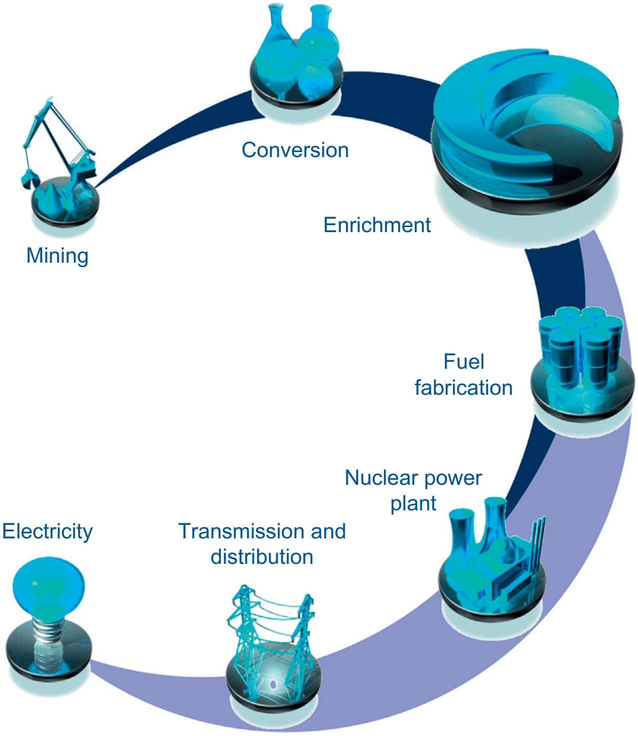


Figure 12.9 The nuclear supply chain.
Source: URENCO.

Figure 12.10 Pictures of URENCO enrichment facilities.
Source: URENCO.

URENCO owns a 50% share of Enrichment Technology Company with AREVA of France holding the remaining 50% share. Enrichment Technology Company is responsible for building and supplying gas centrifuge machines to both URENCO and AREVA.

Commercial gas centrifuge operations commenced at both Capenhurst and Almelo in 1976. The Gronau plant started up in 1985 and the first cascades at Eunice came online in 2010.

URENCO's major expansion of capacity was over the 15 year period 2000–15 when its gas centrifuges replaced tranches of out-dated gas diffusion technology in the United States and France. Going forward, URENCO's focus is expected to be on maintaining current capacity. See also URENCO Annual Report and Accounts (2014).

12.2.3.2 AREVA

AREVA is a French full service nuclear company, involved in all parts of the fuel cycle from uranium mining to fuel fabrication together with nuclear power plant supply. Its headquarters are in Paris.

AREVA operate gas centrifuge facilities (the Georges Besse II Enrichment Plant) at Tricastin in Provence, France. The South Unit began operations in 2011, the North Unit in 2013. By 2016, the combined capacity of the two units will reach 7500 tSWU pa.

AREVA bought a 50% share in Enrichment Technology Company from URENCO in 2006. The centrifuges installed in the Georges Besse II Plant are

Figure 12.11 Picture of AREVA Tricastin enrichment facility.
Source: AREVA.

predominantly model TC12, with at least one cascade of an uprated TC12 + variant (Fig. 12.11). See also http://www.areva.com/EN/operations-887/tricastin-site-the-georges-besse-ii-enrichment-plant.html.

12.2.3.3 Russia

Russia has four operating enrichment plants with a total capacity of 24,000 tSWU pa: (1) Novouralsk, near Yekaterinburg in the Urals, (2) Zelenogorsk (previously known as Krasnoyask—45), (3) Seversk near Tomsk, and (4) Angarsk near Irkutsk, the last three all in Siberia, (Fig. 12.12, Table 12.1).

All plants are equipped with various generations of Russian developed gas centrifuges. Machines are currently manufactured at Kovrov Mechanical Plant in Vladimir region and Urals Gas Centrifuge Plant in Novouralsk prior to shipment to and installation at the plant of use. Machines were also made at Tocmash up to 2012. The last sixth and seventh generation machines were installed in 2005. Eighth generation equipment was installed 2004–12. Ninth generation machines have been installed from 2013.

For more detailed information, see Bukharin (January 2004). See also http://www.world-nuclear.org/info/Country-Profiles/Countries-O-S/Russia--Nuclear-Fuel-Cycle/#Enrichment.

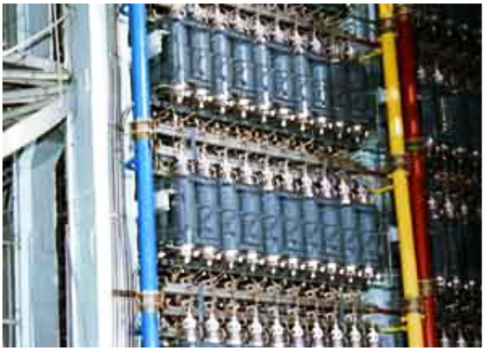


Figure 12.12 Picture of Russian gas centrifuges.
Source: Tenex.

Table 12.1 **Individual Russian Enrichment Plant Capacities**

Plant	Capacity (1000 tSWU pa)
Novouralsk	10.0
Zelenogorsk	8.7 (expanding to 12)
Seversk	3.0
Angarsk	2.6
Total	24.3

In 2013, a TVEL-Kazakh Joint Venture acquired a 25% share of the Novouralsk facility with an entitlement to half the output. This means Kazatomprom in Kazakhstan can access up to 2500 tSWU pa enrichment capacity.

12.2.3.4 China

China has three operating gas centrifuge factories; Hanzhun in Shaanxi province, (Fig. 12.13), Langzhou in Gansu province, (Fig. 12.14), and Emeishan in Sichuan province.

China's first gas centrifuge facilities were supplied by Russia with sixth generation Russian machines installed. The first Russian supplied centrifuge plant of 500 tSWU pa capacity started operation at Langzhou in 2001. Two modules came into operation at Hanzhun 1997–2000, providing addition of 500 tSWU pa capacity. A further 500 tSWU pa of Russian supplied capacity was commissioned in 2011.

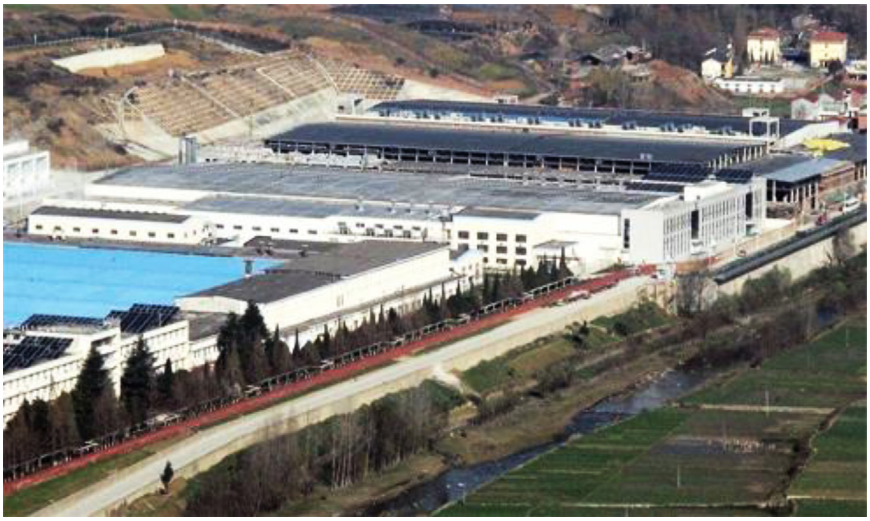


Figure 12.13 Picture of Hanzhun enrichment facility.
Source: http://lewis.armscontrolwonk.com/archive/6826/chinas-new-centrifuge-plants.

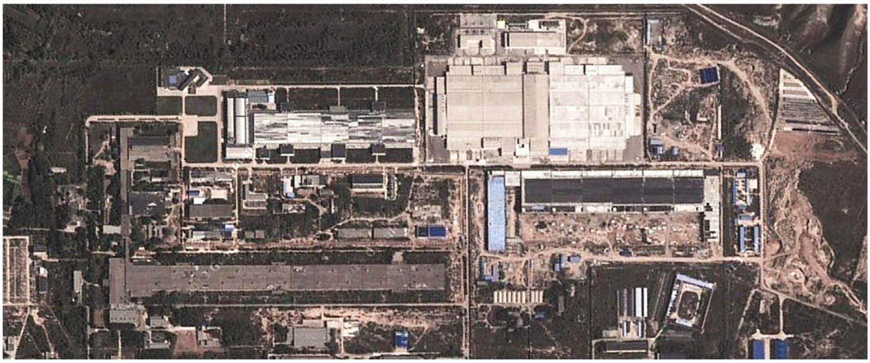


Figure 12.14 Google Earth image of Langzhou facility.

China has and continues to develop its own indigenous gas centrifuge technology. The first plant with Chinese manufactured machines installed was brought into operation in 2013. And is thought to have a capacity of about 500 tSWU pa. Therefore total Chinese capacity at the end of 2014 was thought to be about 2000 tSWU pa and have reached around 2800 tSWU pa by the end of 2015.

With its ambitious nuclear reactor construction program, of all the enrichers, China is expected to continue to expand its enrichment capacity, based on its own indigenous technology, to at least meet its own internal needs and sell some surplus enrichment into the global market. China aims to be fully independent in enrichment capability including R and D, engineering, manufacturing and operating. See also http://www.world-nuclear.org/info/Country-Profiles/Countries-A-F/China--Nuclear-Fuel-Cycle/.

12.2.4 Other countries with operating civil enrichment facilities

12.2.4.1 Brazil

Brazil has a civil enrichment facility at Resende. The facility uses gas centrifuge technology developed by the Brazilian navy at Aramar in the 1980s for a naval propulsion program.

The facility at Resende is operated by Industrias Nucleares do Brazil (INB) and is intended to serve much of the enrichment needs of Brazil's Angra reactors. The Resende plant was officially opened in 2006 and Stage 1 has seen ramp up to four modules totaling 115 tSWU pa capacity. INB plans to reach 200 tSWU pa capacity by 2018. See also http//www.world-nuclear.org/info/Country-Profiles/Countries-A-F/Brazil/.

12.2.4.2 Japan

Uranium enrichment in Japan is undertaken by Japan Nuclear Fuel Ltd (JNFL) at Rokkasho, Aomori prefecture. The facility has used Japanese indigenous gas centrifuges of various generations.

The first generation plant operated 1992–2010 with a capacity of up to 1050 tSWU pa. A second generation plant using machines with carbon fiber rotors started operating in 2011. The ultimate aim is to provide a capacity of 1500 tSWU pa. See also http//www.jnfl.co.jp/English/business/uran.html.

12.2.5 Other countries with uranium enrichment capabilities

12.2.5.1 Argentina

INVAP operated a small (20 tSWU pa) gas diffusion enrichment facility in Argentina 1983–89. The plant was unreliable and produced very little LEU. In 2006, Comision Nacional de Energia Atomica (CNEA) said it wanted to recommission the plant using its own advanced diffusion technology, which was said to be competitive, and develop up to 3000 tSWU pa capacity. The facility was officially inaugurated on 1 December 2015. See also http://www.world-nuclear.org/info/Country-Profiles/Countries-A-F/Argentina/.

12.2.5.2 Pakistan

A small (15 tSWU pa) uranium centrifuge plant at Kakuta has been operated since 1984. It does not have any apparent civil use and was expanded threefold in 1991. Another plant is reported to be at Gadwai. It is not under civil safeguards. See also http://www.world-nuclear.org/info/Country-Profiles/Countries-O-S/Pakistan/.

12.2.5.3 India

A small centrifuge enrichment plant, is operated by the Department of Atomic Energy (DAE) Rare Materials Plant (RMP) at Ratnahalli, near Mysore, with some supply to research reactors. It started up in 1992 and is apparently being expanded to 25 tSWU pa. DAE in 2011 announced that it would build an industrial-scale centrifuge complex in Karnataka having both civil and naval purposes. India's enrichment plants are not under civil safeguards. See also http://www.world-nuclear.org/info/Country-Profiles/Counties-G-N/India.

12.2.5.4 Iran

Iran's uranium enrichment capability and capacity has been a topic of international controversy and negotiations for some years, the debate being potential military versus civil purpose to Iran's program. More detail can be read in http://www.world-nuclear.org/info/Country-Profiles/Countries-G-N/Iran/.

Table 12.2 summarizes what is publically known about Iran's uranium enrichment capability.

The Iranian capacity is comprised mainly of IR-1-type gas centrifuges (which are based on Pakistan's P1 design) with variants such as IR-2 to IR-6 reported as developments.

The first facility, PFEP, started operations in 2003. Operations at PFEP and FEP are under international civil safeguards, though monitoring is constrained.

Table 12.2 **Iranian Enrichment Plant Capacities**

Facility	**Capacity (tSWU pa)**
Natanz Pilot Fuel Enrichment Plant (PFEP)—above ground	<1
Natanz Fuel Enrichment Plant (FEP)—below ground	Approx. 6.5 (Nov. 2013)
Fordow Fuel Enrichment Plant (FFEP)—below ground	<1

12.2.6 Civil enrichment services demand/supply balance

Section 12.1.3 detailed the forward demand for uranium enrichment services.

In Section 12.2, plants and their capacities to provide civil nuclear enrichment services have been described. This allows overlay of available supply against demand for the period 2015–24. However, if this is done simplistically, without some key additional considerations, it would immediately appear that there is a significant excess of enrichment services capacity over demand. There are three other main factors to take into account in considering the real demand/supply balance: (1) tails re-enrichment, (2) enriched product inventories, and (3) civil utilization of ex-military materials. Each of these factors is discussed in turn.

12.2.6.1 Tails re-enrichment

In most commercial enrichment contracts, the customer agrees to supply the enricher with a given quantity of feed material in return for a given quantity of enriched product and pays for the services provided by the enricher. The tails arising from the enrichment performed are owned by the enricher. The enrichment contract will specify the tails assay, quite typically in the range 0.2–0.3% ^{235}U. Clearly the tails still contain residual ^{235}U and it is possible to use such tails as feedstock in a further enrichment cycle, producing additional enriched product and "tails of the tails" or "secondary tails." Such two-stage enrichment is illustrated in Fig. 12.15.

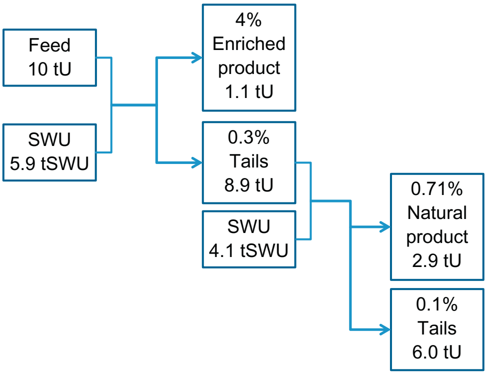


Figure 12.15 Re-enrichment of tails.
Source: URENCO.

The economics of tails re-enrichment depend, among other factors, on the price of natural uranium feedstock, the price of enrichment services, and the marginal costs of operating enrichment facilities. However, in the case of any surplus of enrichment capacity, there are drivers to devote some enrichment capacity to the re-enrichment of tails to regenerate natural uranium feedstock or additional enriched product for sale.

An alternative to re-enriching tails is a mode of operating enrichment plants known as "underfeeding." In this mode, an enricher can choose to use more SWU than specified in the contact to provide the required quantity of enriched product to the customer, but strip the tails to a lower assay than specified in the contract and thereby consume less feedstock than is provided by the contract. The saved feedstock is then owned by the enricher and can be sold on the market. The principle of underfeeding is illustrated in Fig. 12.16.

Underfeeding and tails re-enrichment are somewhat interchangeable in terms of their utilization of enrichment capacity and both are labeled tails re-enrichment in assessing demand/supply balance. Because it is desirable to keep capital intensive gas centrifuge plants in continuous operation, enrichers tend to underfeed/re-enrich tails at times when demand for primary enrichment is suppressed, such as the post-Fukushima period (see Section 12.2.6.2).

In the case that natural uranium was cheap compared to enrichment services, based on economics, enrichers could choose to "overfeed" plants. This involves enrichers acquiring additional feedstock, compared to that supplied in a contract, and using less SWU than specified in the contract to provide the customer with the required quantity of enriched product. Overfeeding has only been undertaken when

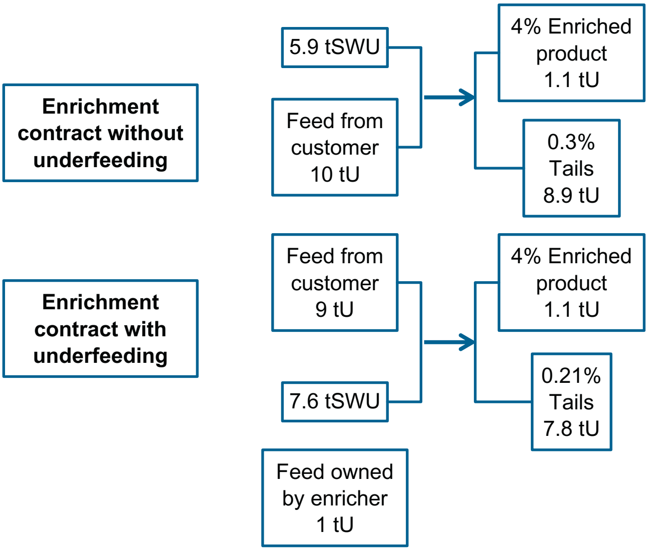

Enrichment contract without underfeeding
5.9 tSWU
Feed from customer 10 tU
4% Enriched product 1.1 tU
0.3% Tails 8.9 tU
Enrichment contract with underfeeding
Feed from customer 9 tU
7.6 tSWU
4% Enriched product 1.1 tU
0.21% Tails 7.8 tU
Feed owned by enricher 1 tU

Figure 12.16 Explanation of underfeeding.
Source: URENCO.

uranium is cheap and/or enrichment capacity is in short supply compared to demand, or if, as with gas diffusion in the past, the enrichment process is expensive to operate.

12.2.6.2 Enriched product inventories

Historically, for various reasons, a number of parties, including governments and utilities, have held varying inventories of enriched product (to provide a buffer against supply chain interruption, for example).

Furthermore, post-Fukushima enrichment services contracted for Japanese reactors, which have been shutdown for at least 4 years, have continued to some extent with consequent buildup of product stocks.

Part of the forward use of such inventories to fulfill demand has to be added on the supply part of the equation; obviously dampening the demand for enrichment services from primary production.

12.2.6.3 Civil utilization of ex-military materials

A further source of existing enrichment inventory that can be utilized in the civil fuel cycle is material derived from downblending HEU surplus to requirements because of the decommissioning of nuclear weapons.

12.2.6.3.1 "Megatons to Megawatts": The Russian HEU deal

A celebrated initiative called the "Megatons to Megawatts" Programme from 1993 to 2013 saw 500 t HEU from decommissioned Russian weapons diluted in Russia to 14,500 t LEU and shipped to the United States for use in commercial power reactors.

The agreement between the United States and Russian governments was made in 1993 as part of arms reduction initiatives. In 1994, the United States Enrichment Corporation (USEC) and Tenex were made executive agents, respectively, for the US and Russian governments to progress the program.

The agreement was essentially an enrichment deal totaling about 90,000 tSWU. About 150,000 t natural uranium was exchanged for the LEU of which 112,000 t was sold on the world market and 38,000 t was sent to Russia.

The last of the 500 t HEU was downblended at Zelenogorsk in Aug. 2013 and shipped to the United States in Nov. 2103. This marked the end of the "Megatons to Megawatts" program.

Russia has other surplus military HEU which it may downblend for its own civil use. See also http://world-nuclear.org/info/Nuclear-Fuel-Cycle/Uranium-Resources/Military-Warheads-as-a-Source-of-Nuclear-Fuel/.

12.2.6.3.2 US HEU disposition

For its part, the US government initially declared just over 174 t HEU surplus from military stockpiles. Downblending and release to the civil market has proceeded in batches and whereas the Russian HEU deal is now part of history, release of US government ex-weapons inventory into the civil market needs to be factored into the forward supply/demand balance.

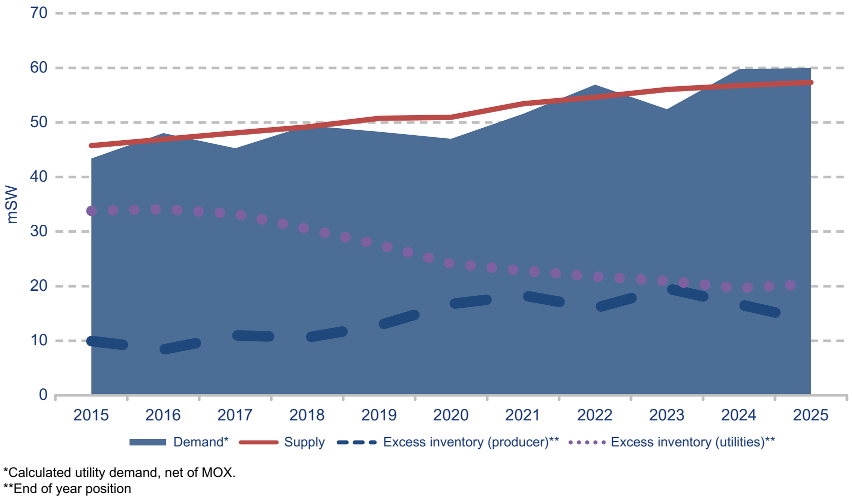


Figure 12.17 A view of the demand/supply balance 2015–25.
Source: URENCO.

12.2.6.4 Overall demand/supply balance forecast 2015–25

Taking into account primary demand, primary enrichment services supply, and the key modifiers discussed previously; tails re-enrichment, inventory use, and civil utilization of ex-military materials, one view of the demand/supply balance for enrichment services over the period 2015–25 is shown in Fig. 12.17.

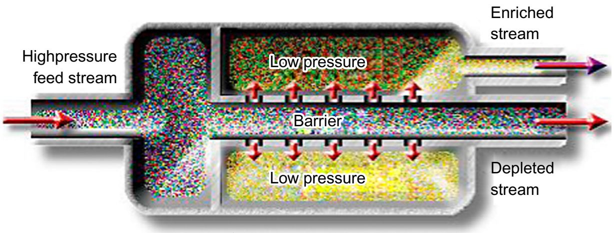
Tails re-enrichment essentially brings enrichment services supply in balance with demand.

12.3 Historic technologies

The focus of this chapter is to consider uranium enrichment now and in the future, but for completeness, this section briefly describes historic uranium isotope separation technologies.

12.3.1 Gas diffusion

The principle of gas diffusion to separate ^{235}U and ^{238}U is based on forcing uranium (again in the form of uranium hexafluoride) through a semipermeable barrier. The lighter $^{235}UF_6$ will tend to travel slightly more easily (faster) through the barrier than the heavier $^{238}UF_6$. As with gas centrifuges, the degree of separation by passage through a single barrier is small, hence the gas diffusion process needs to be repeated through many stages to achieve the enrichments required for nuclear power plants.



Characteristics:

- **Low separation efficiency requires hundreds of stages**
- **High electricity consumption**
- **Significant uranium hold-up in cascades**
- **Fixed capacity—not modular**

Figure 12.18 Gas diffusion.
Source: Portsmouth Virtual Museum.

Fig. 12.18 represents the principle of the gaseous diffusion process.

Gas diffusion was the first uranium isotope separation technology deployed on an industrial scale, reaching back to the United States in the 1940s. In addition, the United Kingdom, France, Russia, and China have all utilized gas diffusion for both military and civil enrichment. (Argentina has also used gas diffusion on a small scale, see Section 12.2.5.1.)

Gas diffusion plants use large compressors to drive uranium hexafluoride through the diffusion barriers at pressure. They consume significantly more electricity than even the early generation equivalent capacity gas centrifuge plants. Gas diffusion plants are monolithic rather than modular in construction and have high in-process inventories (many tonnes) of material again in sharp contrast to gas centrifuge plants, which operating under high vacuum and have very low (kilogram) quantities of material held up in-plant. By 2013, all commercial gas diffusion plants in the world had shutdown, being wholly superseded by the superior economic and flexible gas centrifuge technology on a global basis. See also http://world-nuclear.org/info/Nuclear-Fuel-Cycle/Conversion-Enrichment-and-Fabrication/Uranium-Enrichment/.

12.3.2 Electromagnetic process

A very early technology was electromagnetic isotope separation (EMIS), using devices called calutrons (in effect large-scale mass spectrometers).

In calutrons, ions of ^{235}U and ^{238}U are separated because they follow different curved paths when they move through a magnetic field. The process is very energy intensive, about 10 times that of diffusion.

EMIS was developed in the 1940s as part of the US Manhattan Project, but was abandoned in favor of gas diffusion.

Calutrons were found in Iraq during the Gulf War in 1992, indicating the existence of a military program. See also http://world-nuclear.org/info/Nuclear-Fuel-Cycle/Conversion-Enrichment-and-Fabrication/Uranium-Enrichment/.

12.3.3 Aerodynamic processes

Two aerodynamic processes were brought to demonstration stage around the 1970s. One is the jet nozzle process, with a demonstration plant built in Brazil, and the other is the Helikon vortex tube process developed in South Africa. Neither is in use now.

The processes depend on a high-speed gas stream bearing UF_6 being made to turn through a very small radius, causing a pressure gradient similar to that in a centrifuge. The light fraction can be extracted towards the center and the heavy fraction towards the outside. Thousands of stages are required to produce enriched product for a reactor. Both processes are energy intensive. See also http://world-nuclear.org/info/Nuclear-Fuel-Cycle/Conversion-Enrichment-and-Fabrication/Uranium-Enrichment/.

12.3.4 Chemical process

One chemical process has been demonstrated to pilot stage but not used. The French Chemex process exploited a very slight difference between the ^{235}U and ^{238}U isotopes valence change behavior in oxidation/reduction using aqueous (III valence), and organic (IV valence) phases. See also http://world-nuclear.org/info/Nuclear-Fuel-Cycle/Conversion-Enrichment-and-Fabrication/Uranium-Enrichment/.

12.4 Future technologies

12.4.1 The American centrifuge (USEC and Centrus)

The American centrifuge is a large gas centrifuge, which has been under development/demonstration in the United States over several decades.

Historically, uranium enrichment in the United States was carried out by the Department of Energy (DOE). The DOE operated gas diffusion plants at Oak Ridge and Paducah in Tennessee, and Portsmouth (also called Piketon) in Ohio. Uranium enrichment operations ceased at Oak Ridge in 1987. The remaining gas diffusion plants were taken over by USEC in 1993 and USEC was privatized through an initial public offering in 1998. The Portsmouth gas diffusion plant stopped enriching uranium in 2001 and the Paducah gas diffusion plant ceased uranium enrichment in 2013.

In Dec. 2013, USEC announced that it had reached agreement with a majority of its debt holders to file a prearranged and voluntary Chapter 11 bankruptcy restructuring in the first quarter of 2014. In Sep. 2014, it was announced that the

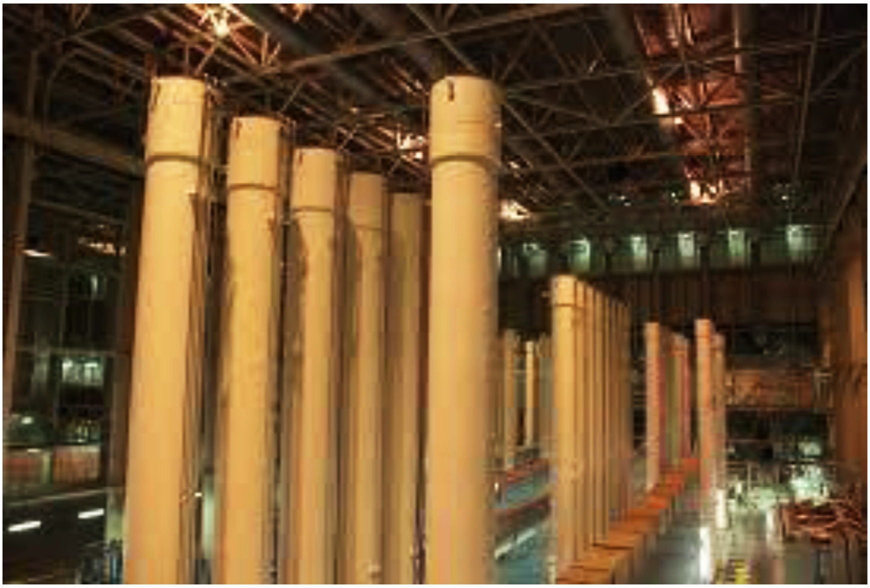


Figure 12.19 Picture of American Centrifuge Project (ACP) cascade.
Source: NEI.

company had emerged from bankruptcy proceedings with a new name, Centrus Energy Corporation.

Centrus is now a contractor to US DOE for the development and deployment of the American centrifuge, when market conditions are appropriate.

The American centrifuge was developed by US DOE in the 1980s. The DOE invested $3 billion over 10 years to develop the technology, built approximately 1500 machines and accumulated more than 10 million machine hours of run time.

US DOE and USEC then sought to develop the alternative laser enrichment Atomic Vapour Laser Isotope Separation (AVLIS) technology (see Section 12.4.2.1), with some $2 billion spent over a 26 year period, before AVLIS was abandoned in 1999 in favor of a return to the American Centrifuge Program.

The current production machine, known as the AC100, has been installed at a test/pilot facility in Piketon. Demonstration cascades with a hundred or so machines have operated since 2007, (Fig. 12.19).

It is possible that an industrial-scale American centrifuge plant will be built in the future, hence its inclusion as a future technology in this chapter. See also http://www.centrusenergy.com/american-centrifuge.

12.4.2 Laser enrichment

Laser enrichment processes fall into two categories: atomic or molecular.

12.4.2.1 Atomic Vapour Laser Isotope Separation (AVLIS or SILVA in France)

The feedstock for the AVLIS process is uranium metal. The metal is heated to form a vapor. Laser light at a very specific frequency is then directed at the vapor such that ^{235}U atoms only are ionized by the ejection of an electron. Positively charged $^{235}U^+$ ions are attracted to a negatively charged collector plate. The ^{238}U atoms in the vapor are not ionized by the impact of the laser light and pass unaffected through the process (Figs. 12.20 and 12.21).

Like all laser isotope separation processes, AVLIS offers the possibility of lower-energy inputs, lower capital costs and high separation factors; but after

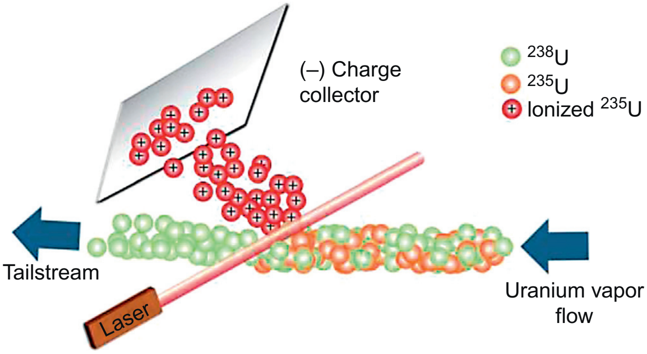


Figure 12.20 AVLIS process.
Source: NRC.

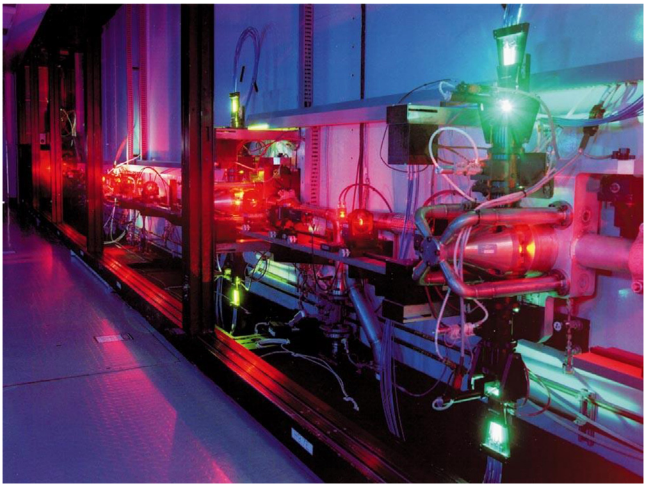
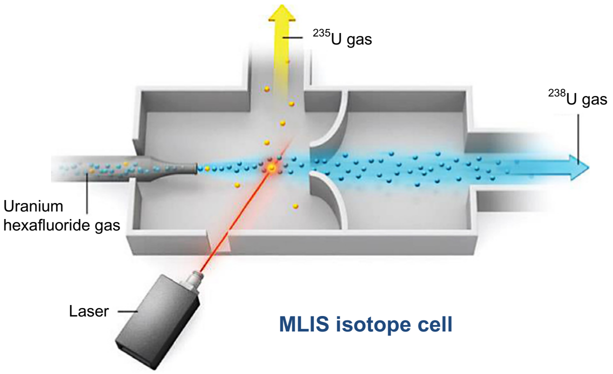


Figure 12.21 Picture of AVLIS.
Source: Wikepedia.

research, not least by URENCO, France, and the United States, these advantages have not proved commercially realizable to date.

Problems thrown up by research include the complexity and reliability of the required laser systems and the robustness of collector systems. Furthermore, because it uses metal feedstock, modification to the global fuel cycle, which is oriented around UF_6 as the feedstock for enrichment processes, would be required. See also http://world-nuclear.org/info/Nuclear-Fuel-Cycle/Conversion-Enrichment-and-Fabrication/Uranium-Enrichment/.



Characteristics:

- **Potentially high separation efficiency**
- **Low electricity consumption predicted**
- **Requires cells to be arranged in cascades**
- **Technology development dependent on laser reliability**

Figure 12.22 Molecular Laser Isotope Separation (MLIS) process.
Source: spectrum.ieee.org.

12.4.2.2 Molecular Laser Isotope Separation (MLIS)

Most molecular processes that have been researched work on the principle of photodissociation of UF_6 to UF_5^+ using tuned laser radiation to break the molecular bond holding one of the six fluorine atoms to a ^{235}U atom. This enables the ionized UF_5^+ to be separated from the unaffected UF_6 molecules containing ^{238}U atoms. Any process using UF_6 fits more readily into the conventional fuel cycle than the atomic process (Figs. 12.22 and 12.23). See also http://world-nuclear.org/info/Nuclear-Fuel-Cycle/Conversion-Enrichment-and-Fabrication/Uranium-Enrichment/.

12.4.2.2.1 SILEX/GLE

Separation of Isotopes by Laser EXcitation (SILEX) is a form of isotope separation developed in Australia, with SILEX Systems Ltd founded there in 1988.

In 1996, SILEX Systems Ltd. licensed its technology exclusively to the USEC for uranium enrichment. Following abandonment of SILEX by USEC in 2003, in favor of concentrating on development of the American centrifuge (see

Figure 12.23 Picture of MLIS.
Source: ic.pics.livejournal.com.

Section 12.4.1), SILEX Systems, in 2007, signed an exclusive commercialization and licensing agreement with General Electric Corporation (GE), in the United States. In 2008, GE spun off global laser enrichment (GLE), to commercialize the SILEX technology. A test loop program was undertaken at GE's facility in Wilmington, North Carolina and plans were announced for the first commercial uranium enrichment facility using SILEX.

Cameco of Canada bought into the project in 2008. In 2012, the US NRC issued a Combined Construction and Operating license for a plant up to 6000 tSWU pa capacity at Wilmington. However, due to the prevailing market conditions, GE decided to reduce funding to GLE and as a result, Cameco reported a full write-down of its investment.

It is possible that an industrial-scale SILEX plant will be built in the future when market conditions are appropriate, hence the inclusion of GLE/SILEX as a future technology in this chapter.

In 2013, GLE submitted a proposal to the US DOE to establish a laser enrichment plant at Paducah to re-enrich DOE-owned tails. The proposed plant capacity was 500−1000 tSWU pa. Negotiations with DOE continued through 2014/15. See also http://world-nuclear.org/info/Nuclear-Fuel-Cycle/Conversion-Enrichment-and-Fabrication/Uranium-Enrichment/.

12.4.2.2.2 CRISLA

Condensation Repression Isotope Separation by Laser Activation (CRISLA) is a variant of MLIS that employs low temperatures to cause UF_6 molecules to condense to form dimers, trimers, etc., and tuned lasers to selectively disrupt such condensation of ^{235}U containing species, thus achieving isotope separation.

For more detail, see Eerkens and Miller (2004).

12.5 Quality control of uranium hexafluoride in enrichment

12.5.1 Feed material

Natural uranium hexafluoride feedstock for enrichment is produced at a number of conversion facilities around the world. Currently the chief facilities in operation are Cameco's Port Hope facility in Canada, Converdyn's Metropolis facility in Illinois, United States, AREVA's Comurhex facilities in Malvesi and Tricastin in France, and conversion facilities in Russia, being consolidated at Seversk.

All natural uranium hexafluoride for enrichment should conform to the 2011 issued standard:

ASTM C787-11 Standard Specification for Uranium Hexafluoride for Enrichment.

Natural uranium hexafluoride feedstock is largely an undifferentiated commodity regardless of the plant of origin and enrichment facilities typically accept quality control documentation, including analysis results, from the supplying converter without resorting to additional sampling and analysis at the enrichment facility.

12.5.2 Enriched product

Enriched product produced at enrichment facilities, forms the feed material to nuclear fuel fabrication plants across the world. The quality standard, which must be met by enriched product, is the 2010 issued standard:

ASTM C996-10 Standard Specification for Uranium Hexafluoride for Enrichment to less than 5% ^{235}U.

The key measurement for enriched product is of course ^{235}U assay. Depending on feedstock, it is sometimes important to particularly check the concentrations of other isotopes such as ^{232}U, ^{234}U, and ^{236}U, to ensure the standard is met. ^{234}U and ^{236}U are neutron absorbers that depress the reactivity of nuclear fuel while the ^{232}U decay chain includes hard gamma emitter ^{208}Tl, which creates additional handling hazards (see Section 12.7).

A variety of sampling and analytical techniques may be deployed at enrichment facilities, including online mass spectrometry, product off-take stream sampling, and analysis, to postproduction homogenization and sampling of full product cylinders.

Figs. 12.24 and 12.25 show a full product cylinder sampling rig at URENCO.

The full cylinder sampling process is as follows:

The cylinder to be sampled is loaded into an autoclave with four sample bottles connected. The autoclave is closed and the cylinder is heated to liquefy and

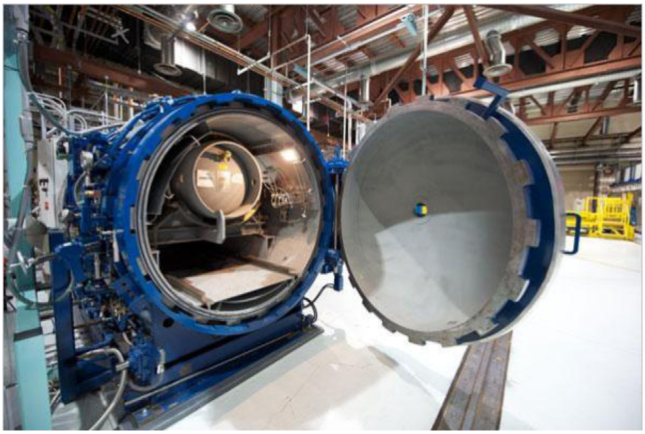


Figure 12.24 30B cylinder inside sampling rig.
Source: URENCO.

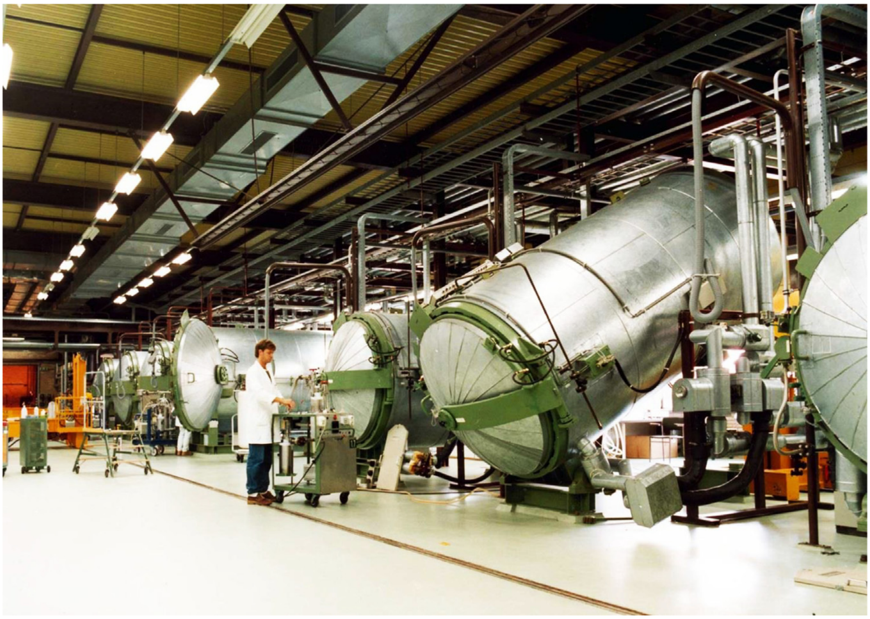


Figure 12.25 Sampling rig in tipped position.
Source: URENCO.

homogenize its contents. One end of the autoclave is raised to allow liquid to flow out of the cylinder valve into the sample bottles. The cylinder is returned to the horizontal and allowed to cool so that the contents resolidify. The autoclave is then opened and the sample bottles removed, with one for the enrichment company, one for the customer, one for the umpire, and one spare. The total sampling cycle time is about 60 h.

12.5.3 Tails

A key point about quality control of tails is its potential to be re-fed for re-enrichment some time in the future. In this case, it becomes feed material and needs to conform to ASTM C787-11, as does natural feedstock.

If tails results from original feed conforming to ASTM C787-11, it is almost certain that the tails will also meet the specification. Online mass spectrometry and tails off-take stream sampling and analysis are periodically used to check the quality of tails.

12.6 Management of tails

The management of tails arising from primary enrichment is an important issue for enrichment service providers.

Three strategies have been deployed by primary enrichers to manage tails:

1. re-enrichment,
2. deconversion,
3. storage pending re-enrichment, deconversion, or some other use.

12.6.1 Re-enrichment of tails

As discussed in Section 12.2.6.1, ^{235}U assays in tails from primary enrichment are quite typically in the range 0.2–0.3% and are suitable for refeed to further strip out useful ^{235}U.

Historically, a significant proportion of enrichment capacity in Russia has been used for the re-enrichment of tails. Russia has not only re-enriched some of its own primary tails but it has also re-enriched primary tails from both URENCO and AREVA enrichment operations. The low ^{235}U assay secondary tails arising from such re-enrichment operations in Russia have been used to dilute HEU derived from decommissioning of Russian nuclear weapons as part of the "Megatons to Megawatts Programme" (see Section 12.2.6.3.1).

Both URENCO and AREVA established conventional enrichment contracts with Russia in which tails from primary enrichment operations at URENCO and AREVA plants in Europe were transported to Russia to form feedstock for Russian plants. In return, URENCO and AREVA received back equivalent natural material or enriched product. Russia took ownership of the secondary tails.

URENCO's contract with Russia to re-enrich tails ran from 1996 to 2010. In total 100,000 tU of URENCO tails from its European plants were processed over this period.

AREVA's contract ran from 1999 to 2010 and in total 60,000 tU of AREVA tails were re-enriched.

Elsewhere, other campaigns of tails re-enrichment have been conducted, the most recent example being the refeed of approximately 9000 t of "high assay" US DOE tails through the Paducah gas diffusion plant immediately prior to its closure in 2013. See also http://www.world-nuclear-news.org/C-Tails_deal_gives_Paducah_another_year-1605127.html.

12.6.2 Tails deconversion

Another option to manage tails is to de-covert tails uranium hexafluoride back to uranium dioxide. This releases a valuable resource, hydrofluoric acid for reuse in chemical processes.

Uranium oxide is the most stable form in which to store tails for the long term and is also suitable for disposition (eg, back into an original uranium mine), should that be a future decision.

Deconversion of tails has been carried out in France since 1984. AREVA have operated four deconversion lines (the "W Plants"), at Tricastin with a capacity of 14,000 tU pa. Over 300,000 tU of tails have been deconverted in AREVA's facility since the start of operations. Most of the tails processed to date has been arisings from AREVA's now closed George Besse I gas diffusion plant. AREVA has also deconverted some URENCO tails. In contracts over the period 2003–14, about 46,000 tU of URENCO tails have been treated.

Deconverted tails in the form of U_3O_8 is stored in 10 t capacity cubic steel containers known as "DV70s." Deconverted French tails are stores at Bessines (Fig. 12.26) and Tricastin. Deconverted URENCO tails are stored by the Dutch national radioactive materials storage organization, COVRA, at Vlissingen in the

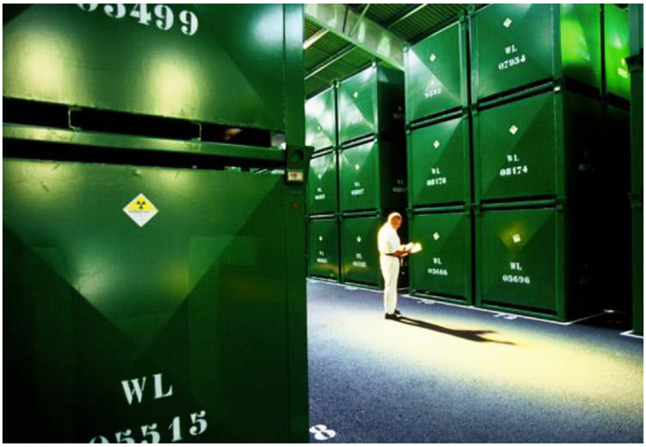


Figure 12.26 Picture of DV70 tails U3O8 containers in store at Bessines.
Source: AREVA.

Netherlands, and will be stored by URENCO at Capenhurst, United Kingdom and Gronau, Germany.

A tails deconversion facility based on AREVA technology has been built at Zelenogorsk in Russia for the treatment of Russian tails. The plant commenced operations in 2009 and has a capacity of 7000 tU pa.

URENCO, through its subsidiary URENCO ChemPlants, is also building a tails deconversion facility based on AREVA technology at Capenhurst in the United Kingdom. Again, with a capacity of 7000 tU pa, the plant is due to commence operation in 2017.

UF_6 is first vaporized in autoclaves and is reacted with steam to form uranyl fluoride. Uranyl fluoride is then reacted with hydrogen at 700°C to yield aqueous hydrofluoric acid for sale to the chemical industry and U_3O_8 powder that is packed into 10 t cubic DV70 containers for storage. The chemical reactions are:

$$UF_6 + 2H_2O \rightarrow UO_2F_2 + 4HF$$
$$3UO_2F_2 + 2H_2O_{(excess)} + H_2 \rightarrow U_3O_8 + 6HF_{(aq)}$$

Two tails deconversion plants have been built by Uranium Disposition Services (UDS), in the United States, one at Portsmouth with a target capacity of about 11,500 tU pa and the other at Paducah with a target capacity 15,500 tU pa. The Portsmouth facility began operations in 2010. The technology deployed is different from the AREVA technology deployed at Tricastin, in Russia and by URENCO. Instead, it is based on original Siemens technology (which is now also owned by AREVA).

Plans for plants to de-convert UF_6 to UF_4 have also been published by Russia (for a plant at Angarsk), and International Isotopes in the United States (for a plant in New Mexico). See also http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Conversion-Enrichment-and-Fabrication/Conversion-and-Deconversion.

12.6.3 Tails storage

Today some quantities of depleted (tails), uranium are used as a carrier for plutonium oxide in MOX fuel and requirements to use tails would go up with any future increase in the use of MOX fuel. Another envisaged future use of some tails is as "blanket" material in fast neutron breeder reactors potentially to be commercially deployed from the mid-21st century. These are additional reasons for enrichers to hold stocks of tails as strategic assets.

Aside from re-enrichment or deconversion, tails depleted uranium hexafluoride may be safely stored for a long period of time in international standard cylinders such as the 48Y with periodic inspection and nondestructive testing (such as

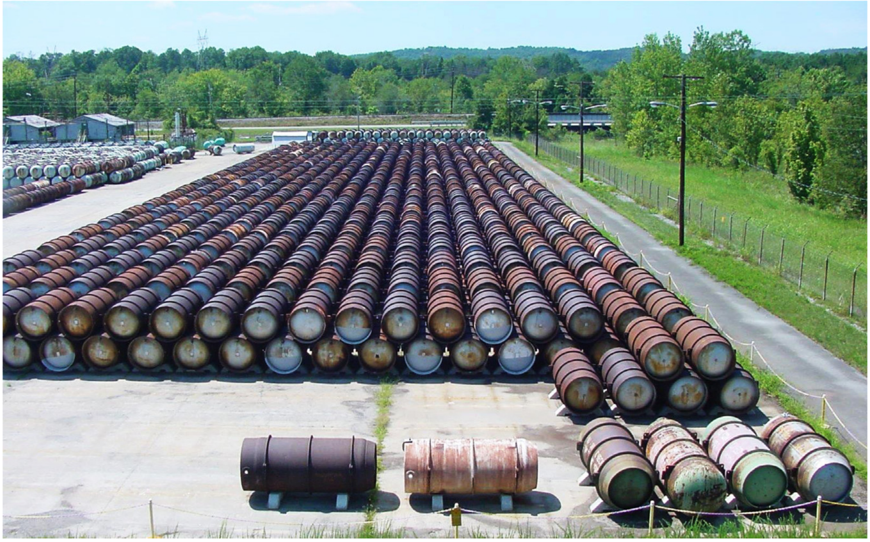


Figure 12.27 Tails UF_6 storage pad.
Source: informaciondesenudo.com.

cylinder wall thickness checks), to confirm storage integrity. A picture of a typical tails hex storage pad is shown in Fig. 12.27.

12.7 Experience enriching reprocessed uranium

As well as freshly mined natural uranium, uranium arising from reprocessing can form feedstock for uranium enrichment operations.

Reprocessed uranium typically contains higher concentrations of the ^{232}U, ^{234}U, and ^{236}U isotopes and other species arising in irradiated material such as technetium (^{99}Tc), a fission product.

Enhanced ^{232}U concentrations are undesirable because its decay chain via ^{228}Th gives rise to species including ^{208}Tl which is a hard gamma emitter creating additional handling hazards. Enhanced ^{234}U and ^{236}U concentrations are also undesirable because the species are neutron absorbers and therefore decrease nuclear fuel efficiency, if present.

Clearly in today's commercial gas centrifuge plants (and in diffusion plants in the past), the process designed to increase the concentration of ^{235}U will also increase the concentration of any ^{232}U, ^{234}U, and ^{236}U present in feedstock relative to ^{238}U.

As described in Section 12.4.2, laser enrichment technologies may be suited to selective enrichment of ^{235}U without coenriching ^{232}U, ^{234}U, or ^{236}U.

Reprocessed uranium has been fed to gas diffusion plants in the past. Due to the large material hold-up, this results in contamination of the plant with reprocessed material, which takes a long time to "flush through." By contrast, with a very small material hold-up in process, gas centrifuge plants are particularly suited to campaigns to enrich reprocessed feedstock and with certain precautions and processes, can switch back to enrichment of un-irradiated natural material with little "memory" of reprocessed material contaminating the cascades.

Some examples of enrichment of reprocessed uranium are as follows:

- Until it shut down in 1982, some 16,000 tU of "magnox-depleted" reprocessed uranium from the UK's first generation magnox reactor fleet was fed to the UK diffusion plant at Capenhurst to increase the ^{235}U assay from about 0.4% to "pseudonatural" around 0.7% assay. The pseudonatural material was then fed through URENCO centrifuge plants at Capenhurst to form about 1650 tU of low-enriched material, which was fabricated into fuel for the UK's second generation advanced gas-cooled reactors fleet.
- Around 1000 tU of reprocessed uranium from La Hague and reconverted to uranium hexafluoride at Tricastin in France has been fed through cascades at URENCO's Almelo plant in the Netherlands to make reprocessed uranium fuel for Kansai in Japan, Synatom in Belgium, and EDF in France. Minor adaptations to the enrichment plant, for example, some remote handling and additional shielding were made to reduce the hazard from enhanced radiation from the feedstock.
- A number of utilities have sent reprocessed uranium arising from their reprocessing campaigns at Sellafield in the United Kingdom and La Hague in France to Russia for processing and fabrication into fuel. In Russia, blending techniques have been deployed to control the concentrations of ^{232}U, ^{234}U, and ^{236}U in finished fuel. The Seversk facility in Russia has been used to enrich some reprocessed uranium feedstock.

Currently, the Russian blending route is the only route available for recycle of reprocessed uranium into fuel. There are no conversion facilities in operation licensed to convert reprocessed uranium to hexafluoride ahead of the enrichment step. A dedicated French reprocessed uranium conversion facility was shut down in 1998. British Nuclear Fuels (BNFL), also in 1998 abandoned a project having partly constructed a dedicated "Line 3" reprocessed uranium conversion facility at Springfields in the United Kingdom.

Fluorides of ^{232}U decay chain elements, including the hard gamma emitting ^{208}Tl, are nonvolatile and may be separated out by feeding reprocessed uranium hexafluoride to a conversion process or by any gaseous transfer of reprocessed uranium hexafluoride from one cylinder to another, effectively "resetting the clock" for the in-growth of ^{232}U decay chain species. Fig. 12.28 shows how new radiation in-growth increases over time, reaching equilibrium after 10 years.

Accordingly, to practically fabricate nuclear fuel from reprocessed uranium, the conversion, enrichment, and fabrication steps need to be executed sequentially with minimum delays, typically within 24 months from conversion to enrichment, and within 6 months from enrichment to fabrication, to minimize radiation doses from handling the material.

Much detail on experience handling reprocessed uranium can be found in IAEA-TecDOC-CD-1630 (2007) available on the Internet.

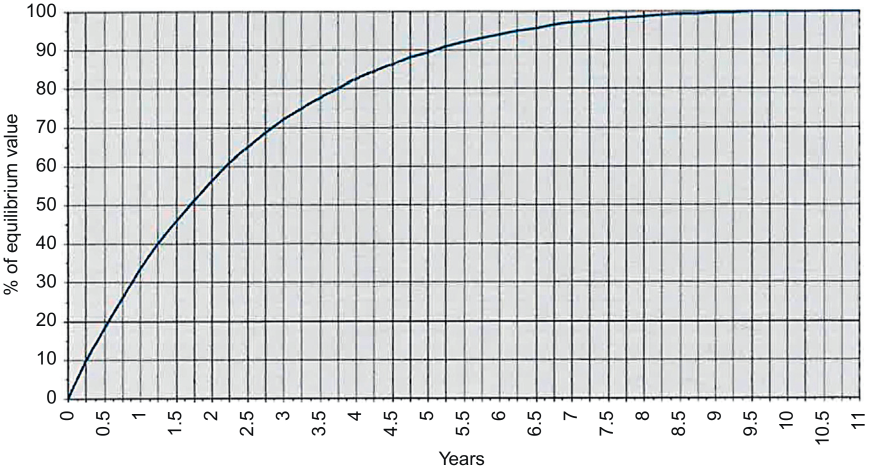


Figure 12.28 Radiation in-growth in newly converted reprocessed uranium.
Source: IAEA-TecDOC-CD-1630 (2007).

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